Gamma-ray transitions in ^{21}Ne†

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γ rays have been studied in coincidence with protons from the ^{19}F(^{3}He, p)^{21}Ne reaction. In addition to known decays, branching ratios have been measured for about 14 weak transitions. By means of $p\gamma$ angular-correlation experiments, spin assignments $J=\frac{1}{2}$ and $\frac{3}{2}$ are confirmed for $E_x=2789$ and 3662 keV, respectively. New spin assignments are $J=\frac{3}{2}$, $(\frac{3}{2})$, and $(\frac{9}{2})$ for $E_x=4684$, 5550, and 6265 keV, respectively. Results are consistent with the unified rotational model of ^{21}Ne.

[NUCLEAR REACTIONS ^{19}F(^{3}He, $p\gamma$), $E_{^3\mathrm{He}}=3.5$ to 7.0 MeV; measured $p\gamma$, $p\gamma(\theta)$. ^{21}Ne deduced γ transitions, branching ratios, J, δ. Natural targets.]

I. INTRODUCTION

The spectroscopy of ^{21}Ne has already been carried to a high degree of development. Ever since Freeman[1] pointed out the aptness of the unified rotational (Nilsson) model in describing ^{21}Ne, several of the authors[2] who have contributed experimental data have also refined the application of this model so that quite a detailed picture has emerged. This is well exemplified in the work of Rolfs *et al.*[3] Application of the multinucleon spherical shell model to the $A=21$ nuclei has been rather limited, since such calculations are often restricted to wave functions of a single harmonic-oscillator quantum number, while it seems to be well established that both the $1p$ subshell ($N=1$) and $1f$ subshell ($N=3$) intrinsic states, in addition to the predominant $2s1d$ shell states, occur at low excitation in these nuclei. One other approach[4] incorporates a wider basis as well as realistic interactions. It is successful in reproducing qualitatively the excitation energies and transition probabilities pertaining to certain even-parity levels.

In the scheme of Rolfs *et al.*[3] all of the levels up to 5 MeV, and several more, can be accounted for as belonging to rotational bands built on the ground state and four other intrinsic states. The assignments of individual levels to particular bands vary in certainty; in some cases they are only tentative. Additional experimental spin determinations and measurements of transition probabilities would help to clarify this situation and would provide further tests for future more inclusive shell-model as well as unified-model interpretations. With this intent, the present work deals with γ-ray transitions in ^{21}Ne following the ^{19}F(^{3}He, p) reaction, with particular attention to some weak transitions.

Most of the γ-ray spectroscopy of ^{21}Ne has been done with the ^{18}O(α, $n\gamma$) and ^{20}Ne(d, p) reactions.[2] The use of ^{19}F(^{3}He, p) permits $p\gamma$ coincidence measurements which identify γ rays with specific levels. It also tends to populate many excited levels with comparable intensities.

II. PROCEDURES

In all of the experiments, two-parameter $p\gamma$ coincidence spectra were measured. Protons were detected in an annular silicon surface-barrier detector 1500 μm thick and 150 mm^2 in area, covered with a foil of Al or Mylar of a suitable thickness in each case to stop elastically scattered ^{3}He ions. Four to six 10-cm × 10-cm NaI(Tl) γ-ray detectors were placed at different angles θ relative to the beam axis, such that values of $\cos^2\theta$ range from 0 to 0.87. With the Notre Dame 4-MV electrostatic generator, 17 angular-correlation experiments were made with ^{3}He beams of 3.5 to 4.2 MeV; in five of these the particle detector was at 0° while in all the rest of the experiments it was at 180°. One experiment at the same accelerator used a 7.0-MeV 50-nA ^{3}He^{++} beam. Fourteen angular-correlation experiments were made with 100- to 150-nA beams between 5.7 and 7.0 MeV at the Notre Dame FN tandem accelerator. The targets were of CaF_2, BaF_2, or sometimes LiF, 50 to 100 keV thick, evaporated onto thin carbon backings. A proton spectrum taken at 5.8 MeV beam energy is shown in Fig. 1.

Initially only four 16 × 64-channel coincidence arrays could be stored simultaneously in the pulse-height analyzer available. Each experiment covered only a part of the range of excitation energies. Experimental facilities gradually evolved until the last of these data were taken as six 128 × 256-channel arrays stored in a magnetic disc connected

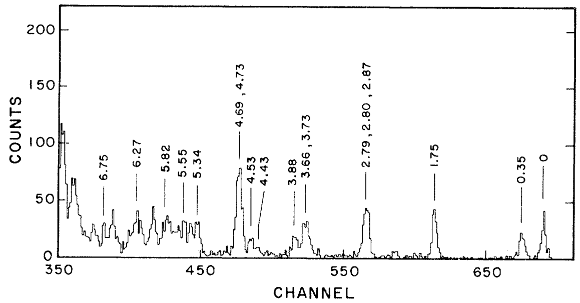

FIG. 1. A portion, 8 to 15 MeV, of the proton spectrum taken with an annular detector at 180°. The detector was 14 mm in diameter, 30 mm from the target, and covered with a 7.0 mg/cm^2 Al foil. A 100 μg/cm^2 BaF_2 target was bombarded with 10 μC of ^{3}He ions at 5.80 MeV. Peaks are labeled with ^{21}Ne excitation energy in MeV. Thinner targets than this were used in some of the work.

with a PDP-9 computer. Additional descriptions of the experimental arrangements and of the basic angular-correlation analysis procedures are to be found in earlier publications.[5,6]

Particular care was taken to optimize the two-parameter spectrum-fitting routines for use with the present data. Thus peak intensities could be extracted consistently, and weak branches could be recognized and measured. In most cases, the branching ratios have been determined from the isotropic term of the Legendre-polynomial fit to the angular dependence of each transition. In the case of weak transitions, the two-parameter spectra taken at the several angles were added together after a scale-matching process and before peak fitting. The matching method followed the approach of Quin.[5] Integral γ-ray channel numbers in the new spectra were connected with nonintegral channel numbers in the original ones by linear transformations. The number of counts corresponding to a nonintegral channel was obtained from a parabolic fit to the contents of the three nearest original channels. This number was then multiplied by the same factor by which the channel width was compressed, so as to conserve total intensity. When the scale-adjusted spectra were added together, the result approximated a true average over the direction of emission of the γ rays. Angular-correlation effects did not vanish exactly, but a correction was made if the angular dependence were known.

When several branches of a given level occur, the pattern of uncertainties may appear unfamiliar because the branching ratios are less strongly correlated than for only two or three branches. Let

TABLE I. Branching ratios, in percent, of excited levels of ^{21}Ne and mixing ratios of transitions among them.

Initial level (keV)	Final level (keV) 0	351	1746	2789	2796	2866	3734	Other
1746	5 ± 1	95 ± 1 [a]						
2789	≤10	≥90						
2796	100	<6						
2866		36 ± 3	64 ± 3 [b]					
3662		59 ± 3		41 ± 3 [c,d]				
3734	81 ± 3	14 ± 3	5 ± 3					
3883	28 ± 3	67 ± 3		0.4 ± 0.2				4 ± 1 (to 3662)
4524	24 ± 3	73 ± 3	3 ± 1					
4684	36 ± 2	60 ± 2			4 ± 2			
4726	<1	80 ± 2		<1	20 ± 2			
5334		88 ± 2				8 ± 2		4 ± 1 (to 3883)
5430		72 ± 4	19 ± 3			9 ± 2		
5525			(100)					
5550	37 ± 8 [e]	16 ± 5		9 ± 3	13 ± 5		16 ± 5	9 ± 3 (to 4524)
5691	38 ± 3 [e]				51 ± 3			11 ± 3 (to 4726)
5823			7 ± 2			56 ± 6		37 ± 6 (to 3883)
6169			(64)				(36)	
6265		17 ± 9	12 ± 7			66 ± 13 [f]		5 ± 3 (to 3883)
6447						(10)		(90) (to 4432)

[a] $\delta = 0.12^{+0.11}_{-0.05}$.
[b] $\delta = 0.08 \pm 0.06$.
[c] Total to 2789- and 2796-keV levels, unresolved.
[d] $\delta = -0.10 \pm 0.06$.
[e] These γ rays were not observed in the present work. See text.
[f] $\delta = -0.8^{+0.7}_{-0.5}$ if $J_i = \frac{9}{2}$.

B_i be the branching ratio derived from intensity I_i and associated efficiency ϵ_i. A formula for the uncertainty ΔB_i can be obtained by combining in quadrature the uncertainties in intensities and efficiencies. The result is $\Delta B_i/B_i = [(1-2B_i)e_i^2 + \sum B_k^2 e_k^2]^{1/2}$, where the sum is taken over all branches and $e_k^2 = (\Delta I_k/I_k)^2 + (\Delta\epsilon_k/\epsilon_k)^2$. The relative efficiency uncertainties $\Delta\epsilon/\epsilon$ are nominally 5%, but less when two γ-ray energies lie close to each other.

In the treatment of the angular correlations themselves, use has been made whenever applicable of routines written for the simultaneous analysis of data sets taken at several beam energies (differing in alignment parameter), of angular correlation data for two or more branches from one aligned level, of sequential transitions in a cascade, and all combinations of these. In all cases, an over-all goodness-of-fit indicator χ^2 per degree of freedom is evaluated for hypothetical combinations of as many spins and mixing ratios as are relevant. The analysis followed conventional practice.[5,6] Mixing ratios are quoted in the sign convention of Rose and Brink.[7]

III. RESULTS

A. Branching ratios

Branching ratios of the excited levels of ^{21}Ne determined in this work are presented in Table I. For the previously known transitions these values are generally in good agreement with values from the literature.[2] The 3883 → 2789-keV transition was observed in the spectra summed over γ-ray detectors but with even lower intensity than reported by Pilt *et al.*[11] The value for the 3883 → 3662-keV transition was inferred from the observed intensities of the 3662 → 2789 → 351-keV γ rays since the primary γ-ray energy was too close to the threshold of the discriminators for its intensity to be measured reliably.

Association of a transition to the 3883-keV level with an initial state at 5823 rather than 5821 keV is based upon the concurrent observation of the 5823 → 2866- and absence of the 5821 → 2796-keV lines; these are the known[3] principal decays of these two levels. The full-energy peaks of the 5550 → 0- and 5691 → 0-keV γ rays were out of range in this experiment. Branching ratios for these two levels were calculated by comparing the new weak branches with the 5550 → 351 → 0- and 5691 → 2796-keV lines, respectively, and incorporating the ratios between the strongest branches of each level given by Rolfs *et al.*[3] In some cases, intensities of transitions to the 351-keV level were best determined from the 351 → 0 keV deexcitation radiation with correction for feeding through cascades.

B. Directional correlations

Angular correlations of the two γ rays from the 1746-keV level with protons feeding that state are equally consistent with spin $J=\frac{3}{2}$ or $\frac{7}{2}$. The mixing ratio of the 1746 → 351-keV transition listed in Table I is obtained assuming the $\frac{7}{2}$ assignment of Pelte *et al.*[8]

The $p\gamma$ directional correlations of the radiations 2866 → 1746, (2866 →) 1746 → 351, and 2866 → 351-keV, simultaneously analyzed, restrict the spin of the 2866-keV level to $\frac{5}{2}$ or $\frac{9}{2}$. If it were $\frac{5}{2}$ the mixing ratio of the 2866 → 351-keV transition would be 1.7 ± 1.0. When the lower limit is combined with the lifetime value of Rolfs *et al.*,[9] even if the stated uncertainty in the lifetime were increased to 40%, an $E2$ enhancement in excess of 70 would be required for this transition. Similarly, an $E2$ enhancement larger than 40 would be required for the 2866 → 1746-keV radiation. These considerations weigh strongly against the $\frac{5}{2}$ choice and thus the present results support the $\frac{9}{2}$ assignment originally made by Pronko *et al.*[10]

From the χ^2 analysis of the 3662 → 2789-keV (and unresolved 3662 → 2796-keV) radiation, all spins other than $\frac{3}{2}$ for the initial level may be rejected well beyond the 0.1% confidence limit. This is a direct consequence of the wide variations in the Legendre coefficients A_2 among the several reaction conditions, and does not require prior knowledge of the 2789-keV spin. This confirms the $\frac{3}{2}$ assignment of the 3662-keV level made in another way by Rolfs *et al.*[3] Once the initial-state spin is known, the possibility $J=\frac{3}{2}$ for the 2789-keV level is eliminated by the same angular-correlation analysis, since the inferred mixing ratio $\delta = 0.5^{+0.2}_{-0.05}$ combined with the lifetime[2] implies an $E2$ enhancement in excess of 200. The only other assignment admissible from direct-reaction analysis, $\frac{1}{2}^-$, is the correct one. Again, this confirms by a different method the assignment of Rolfs *et al.*[3]

The 4684-keV level is restricted to $\frac{3}{2}^+$ or $\frac{5}{2}^+$ by the analysis of stripping experiments.[2] In the present work, $p\gamma$ angular correlations of the 4684 → 0 and 4684 → 351-keV γ rays both showed the variations in A_2 characteristic of a $\frac{3}{2}$ initial state. The χ^2 analysis of the ground-state transition, shown in Fig. 2, allows the $\frac{5}{2}$ possibility to be rejected at the 0.1% confidence limit, leaving a definite assignment of $\frac{3}{2}^+$.

The 5550-keV level is known to have $J^\pi = \frac{3}{2}^+$ through a polarized-deuteron vector analyzing power experiment.[13] Analysis of our angular-correlation data for the 5550 → 2796-keV transition is in agreement with this result but is not adequate to exclude rigorously other possibilities.

All four branches in the decay of the 6265-keV level go to states with $J \geq \frac{5}{2}$, which is consistent with an unpublished assignment of $\frac{9}{2}$ by Kuhlmann quoted in Ref. 3. The χ^2 analysis of our angular-correlation data in the strong 6265 → 2866-keV branch indicates $J = \frac{9}{2}$ at 65% confidence but also about 1% confidence for $J = \frac{7}{2}$.

IV. DISCUSSION

The arrangement of ^{21}Ne levels into bands according to the Nilsson model has been most fully illustrated by Rolfs *et al.*[3] In particular, the first negative-parity band can be built on the $\frac{1}{2}^-$ level at 2789 keV, which is believed to correspond to excitation of a nucleon from Nilsson orbit 4, a $p_{1/2}$ state, to orbit 7 and pairing it with the valence nucleon. The γ rays newly reported here as 3883 → 3662-, 5823 → 3883-, and 6265 → 3883-keV correspond to the $\frac{5}{2} \to \frac{3}{2}$, $\frac{7}{2} \to \frac{5}{2}$, and $\frac{9}{2} \to \frac{5}{2}$ transitions within this band according to the Rolfs *et al.* proposed scheme. Also the 4684 → 2796-keV γ ray would be the $\frac{3}{2}^+ \to \frac{1}{2}^+$ transition in the first $K = \frac{1}{2}^+$ band (Nilsson orbit 9) and the 5691 → 4726-keV line would be the $\frac{1}{2}^- \to \frac{3}{2}^-$ transition in the distorted second $K^\pi = \frac{1}{2}^-$ band (Nilsson orbit 14). Although a quantitative comparison of calculated and measured transition strengths cannot be made at this time, the observation of these transitions does support the unified rotational model interpretation.

The $\frac{3}{2}^+$ assignment to the 4684-keV level provides a necessary condition for its membership in the $K^\pi = \frac{1}{2}^+$ band. As can be seen from Fig. 2, the mixing ratio of the proposed in-band transition 4684 → 2796-keV is indeterminate, so transition strengths cannot be extracted.

If the probable spin $\frac{9}{2}$ for the 6265-keV level is correct and its parity is the same as that of the 3883-keV level (negative[11]) the $E2$ transition between them would have a strength 5 ± 3 Weisskopf units, not a striking value for an in-band transition. The transition strengths for all branches from this level are compatible with the $\frac{9}{2}^-$ supposition.

All of the present results are compatible with the unified rotational model of ^{21}Ne and with the particular interpretation proposed by Rolfs *et al.*[3] But there are data not yet accounted for. Among others in Table I are six previously unreported transitions from the 5334- and 5550-keV levels, making in all three and six branches respectively. These levels may be the $\frac{5}{2}^+$ and $\frac{3}{2}^+$ members of another distorted $K^\pi = \frac{1}{2}^+$ band built on Nilsson orbit 6. Such a band occurs in ^{23}Na. In ^{21}Ne, the $\frac{1}{2}^+$ bandhead would have to lie near 3.88 MeV in excitation. As yet, there is no evidence for an additional level near this energy.

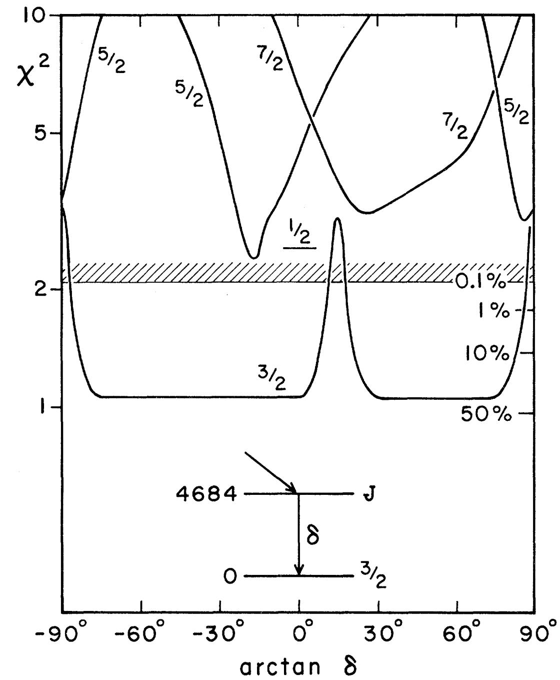

FIG. 2. The normalized goodness-of-fit index χ^2 as a function of mixing ratio δ for the 1, 2 angular correlation of the 4684→ 0-keV γ ray in coincidence with protons feeding the 4684-keV level. Confidence limits are indicated at the right. The 4684→ 351→ 0-keV cascade directional correlations were compatible with this.

Whether the multinucleon shell model with realistic interactions may have equal or greater success in describing ^{21}Ne remains to be seen. Presently available calculations do not provide extensive opportunities for comparison of excitation energies and transition rates. The calculation of Halbert *et al.*[14] was limited to sd-shell basis states. While reasonably successful in reproducing level energies and $E2$ transition rates within the ground-state band, it cannot be compared with much of the body of data presently available.

In another approach, Gunye[4] has carried out Hartree-Fock calculations in a configuration space of the first five major oscillator shells with realistic nucleon-nucleon interactions. The calculations are restricted to axially symmetric deformations. The results presented reproduce faithfully the excitation energies of the ground-state band and the $K^\pi = \frac{1}{2}^+$ band, and $E2$ and $M1$ transition rates between members of the ground-state band. It is to be hoped that such calculations will be extended to include transitions such as those reported herein.

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